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Mechanical properties of high manganese austenitic stainless steel JK2LB for ITER central solenoid jacket material

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Abstract

A suite of advanced austenitic stainless steels are used for the ITER TF, CS and PF coil systems. These materials will be exposed to cyclic-stress at cryogenic temperature. Therefore, high manganese austenitic stainless steel JK2LB, which has high tensile strength, high ductility and high resistance to fatigue at 4 K has been chosen for the CS conductor. The cryogenic temperature mechanical property data of this material are very important for the ITER magnet design. This study is focused on mechanical characteristics of JK2LB and its weld joint.

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Keywords: ITER central solenoid jacket; JK2LB; weld joint; tensile test; fracture toughness; fatigue crack growth rate; fatigue test

1. Introduction

The ITER central solenoid (CS) has to support high electromagnetic forces because it is operated in a high current and high magnetic field. The CS conductor jacket consists of circle-in-square extruded and drawn austenitic stainless steel pipes [1]. When the magnetic field peaks at 13 T, these jackets experience large electromagnetic forces. Additionally, the main load on the CS modules is a cyclic tension generated by the electro-magnetic hoop force

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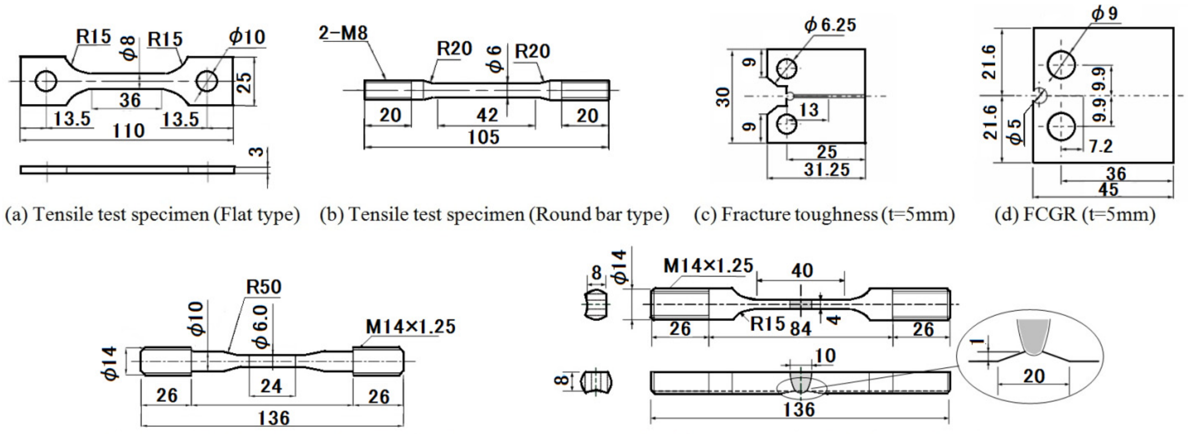
during operation. The CS jacket is required to have a Yield Strength (YS) ≥ 850 MPa, an Ultimate Tensile Strength (UTS) ≥ 1150 MPa, an Elongation (EL) ≥ 25 %, a fracture toughness $K_{IC}(J)$ ≥ 130 MPa$\sqrt{m}$ and a fatigue life of 60,000 cycles at 4 K following prior cold work and a Nb_3Sn superconductor reaction heat treatment (650 °C - 200 h). In addition, the jacket material needs to have a lower integral thermal contraction from room temperature to 4.5 K than conversional stainless steel (-0.3%).

The Japan Atomic Energy Agency (JAEA) has developed a low carbon and boron added 0.03C-22Mn-13Cr-9Ni-1Mo-0.12N-0.003B steel (JK2LB) [2-11] which satisfy above requirements for use as the conductor jacket for the ITER CS in collaboration with Kobe Steel Co., Ltd.

To accumulate the mechanical properties database of JK2LB as a new structure material, mechanical properties, such as tensile tests, fracture toughness tests ($K_{IC}(J)$), fatigue crack growth tests and fatigue tests (*S-N*) at 4.2 K (liquid helium) are characterized. For the fatigue testing of welded joint, specimens were machined as-welded to evaluate the real fatigue characteristics including stress concentration at weld joints.

2. Jacket and test sample

The JK2LB jacket is a circle-in-square tube with outer dimension of 51.3 mm and inner diameter of 35.1 mm. JK2LB jackets are jointed by TIG welding using filler wire and rod made of JK2LB. The jackets are compacted to outer dimension of 49.0 mm from 51.3 mm. To follow the same fabrication recipes of a CS coil, the following works were applied: (i) compaction to 49 mm square, (ii) R2000 mm bending by roll bender, (iii) straightening, (iv) R1300 mm bending by roll bender, (v) straightening, and (vi) aging heat treatment (650 °C - 200 h). After the heat treatment, tensile test specimens, fracture toughness test specimens, FCGR test specimens and fatigue test specimen were machined from the jacket as shown in Fig. 1. Tensile test specimens of flat type were cut from a thin wall. Round bar type were cut from the corner part. In addition, the specimens were removed from the jacket sections and weld joint as shown in Fig. 2.



(a) Tensile test specimen (Flat type) (b) Tensile test specimen (Round bar type) (c) Fracture toughness (t=5mm) (d) FCGR (t=5mm)

(e) Fatigue test specimen (Round bar type) (f) Fatigue test specimen (As-welded type)

Fig. 1. Shape of mechanical test specimens.

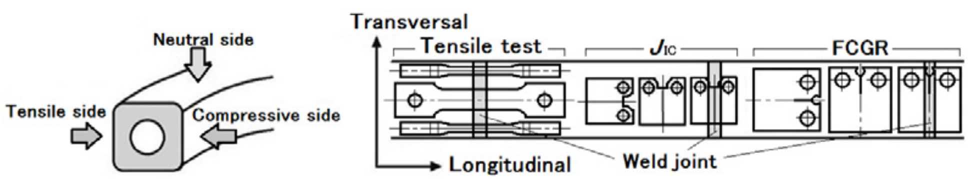


Fig. 2. Major example of the specimen location removed from the jackets section and weld joint.

3. Mechanical test results

3.1. Tensile test results of the JK2LB weld joint

Tensile tests for a JK2LB weld joint were carried out at 4 K (liquid helium) according to JIS Z 2277. The results of tensile tests are shown in Fig. 3. Results of tensile tests satisfied the requirements for the ITER CS conductor jacket, which are more than 850 MPa of yield strength, more than 1150 MPa of ultimate tensile strength, and more than 25 % of elongation. And, the difference between corner section, twin wall part, tensile side or compressive side are small.

3.2. Fracture toughness test results of a JK2LB jacket section and weld joints

Fracture toughness J_{IC} tests were carried out in 4 K (liquid helium) according to JIS Z 2284. The crack length was measured by a clip gauge during test. The J-integrals were measured by the single specimen method, and then J_{IC} was converted into $K_{IC}(J)$ values using a conventional equation of JIS Z 2284.

The J_{IC} test results are shown in Fig. 4. For the jacket section, results of the longitudinal direction are markedly lower than the transversal direction. As for the transversal direction of jacket sections and weld joints, the notch direction of these samples is same direction. However, these results showed different trends, which means that the weld joints were lower than jacket sections. Even so, $K_{IC}(J)$ values of jacket section and weld joint satisfied the ITER CS jacket requirements, which is more than 130MPa$\sqrt{m}$.

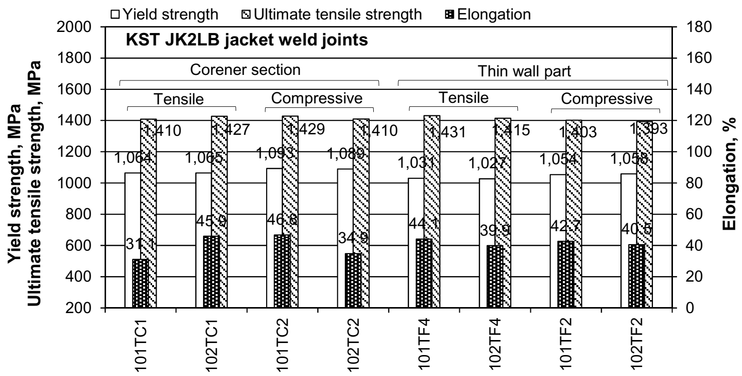


Fig. 3. Tensile test results of the weld joints at 4 K.

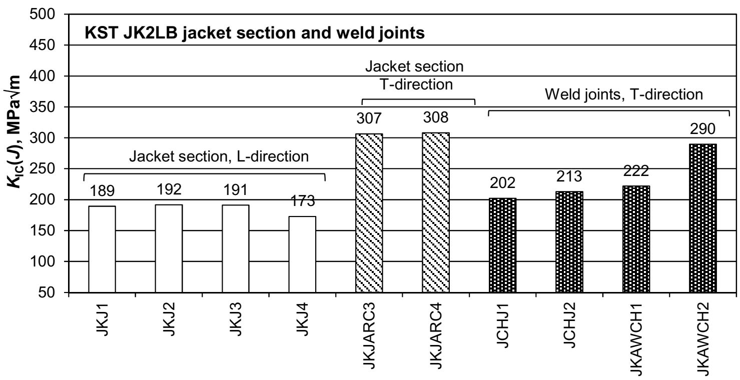


Fig. 4. JIC test results of the jacket sections and the weld joints at 4 K.

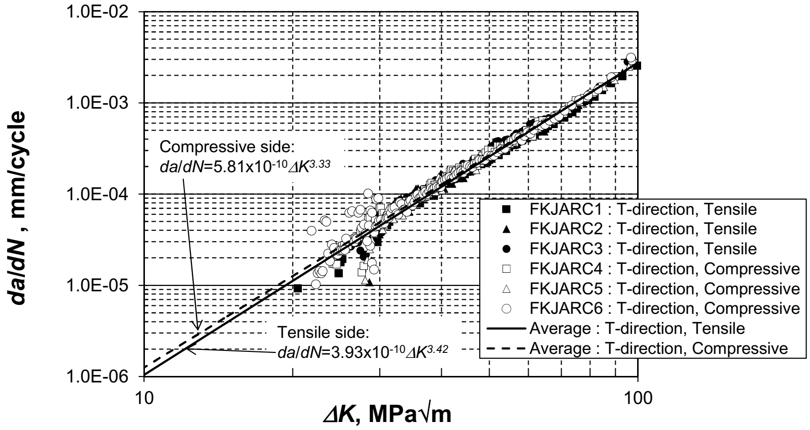
3.3. Fatigue crack growth rate test results of JK2LB jackets section and weld joint

FCGR tests were carried out at 4 K. At first, to grow a pre-crack of about 0.5 mm the specimen was loaded under a sinusoidal stress cycle at a frequency of 10 Hz, a maximum load 7 kN and a load ratio R = 0.1. After a pre-crack grew up, the maximum load was changed to 5 kN or 6 kN.

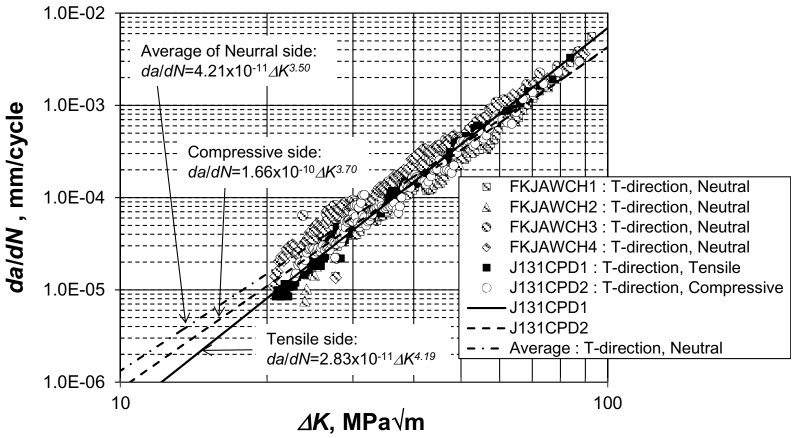
The FCGR results are shown in Fig. 5. The results are shown in terms of the fatigue crack growth rate (*da*/*dN*, mm/cycle) as a function of amplitude of stress intensity factor (ΔK, MPa$\sqrt{m}$), based on Paris's law following equation (1).

$$da/dN = C \cdot \Delta K^{m} \, . \tag{1}$$

As for the jacket sections, the results indicated very comparable regardless of the cutting position and the notch direction of the specimen. However, as for the weld joints, specimen from the tensile side, J131CPD1, exhibits a different slope. This means that crack growth in the tensile side of the bending process is faster than at the compressive side. In other words, this result shows some dependences of FCGR on the cut position and direction of the specimens. This tendency might have been influenced by the bending and stretching process. At any rate, the measured fatigue crack growth rates are low enough to achieve the operation cycle of the CS coil.



(a) Jacket section



(b) Weld joint

Fig. 5. Fatigue crack growth test results of the jacket sections and the weld joints at 4 K.

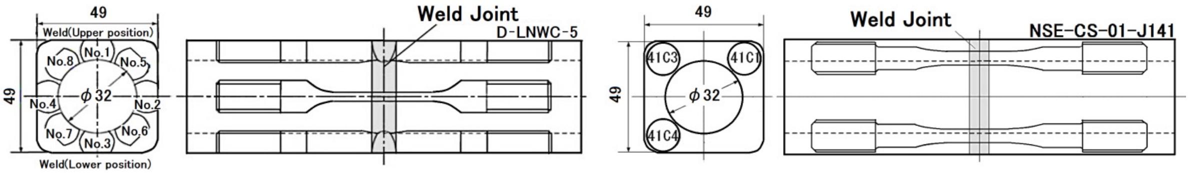
3.4. Fatigue (S–N) characteristic of JK2LB weld joint

For fatigue test at 4 K, two kinds of specimens shown in Figs. 1 (e) and (f) were tested. The specimens of the as-welded type were machined as-welded to evaluate real fatigue characteristic including stress concentration at the weld joint, and tests were carried out. The cut locations of as-weld type specimens are shown in Fig. 6 (a). Furthermore, three specimens of round bar type were tested to confirm the influence of the stress concentration. Locations of round bar type specimens are shown in Fig. 6 (b). These specimens were loaded under a sinusoidal stress cycle at a frequency of 1 Hz and a load ratio R = 0.1. The test load was controlled by a displacement sensor. The *S-N* diagram concerning equivalent stress amplitude is shown in Fig. 7, which also includes the JK2LB jacket sections data from Walsh et al. [10]. In this figure, measured data are converted to equivalent stress amplitude (S_{eq}) using the following modified Goodman equation (2) and applying the actual measured UTS of 1400 MPa (see section 3.1) :

$$S_{eq} = \frac{S_{amp}}{\left(1 - \frac{S_{mean}}{S_u}\right)} \quad , \tag{2}$$

where, S_{amp} is the stress amplitude, S_{mean} is the mean stress, and S_u is the ultimate tensile strength.

The weld joints data obtained from the round bar type specimen and the reference data of jackets sections are very comparable. Note that this is a comparison of the corners of a weld joint of the thin-walled parts of the jacket section. For the as-weld type specimen, the number of cycles-to-failure decreased because of the stress concentration at the weld toe.



(a) As-weld type (b) Round bar type

Fig. 6. Location of fatigue specimens removed from the JK2LB weld joint.

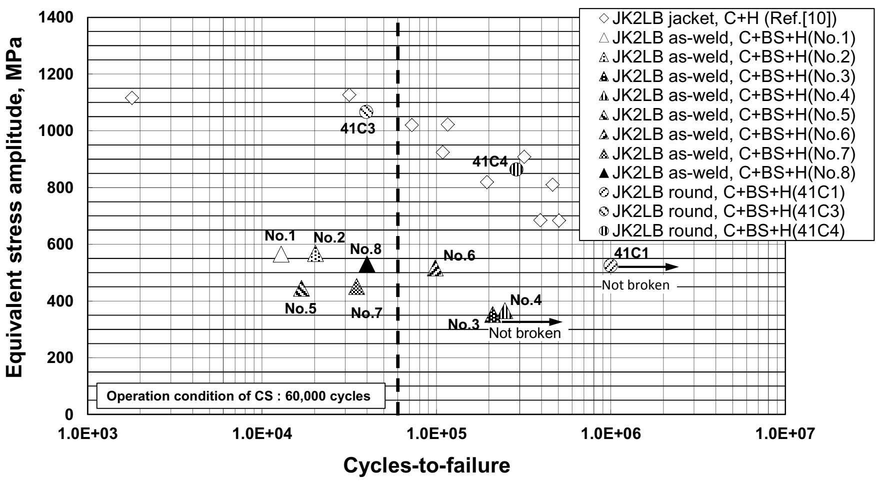


Fig. 7. Result of *S-N* data for JK2LB weld joint.

4. Conclusion

In order to increase the available database for the JK2LB material, mechanical tests at 4 K (liquid helium) were carried out. The results of tensile test satisfied the ITER CS jacket requirements, which are more than 850 MPa of yield strength, more than 1150 MPa of ultimate tensile strength, more than 25 % of elongation, and the fracture toughness $K_{IC}(J)$ is more than the requirement 130 MPa$\sqrt{m}$. For the fatigue crack growth rate test, they are low enough to achieve the operation cycle of the CS coil. In the fatigue testing of a welded joint, specimens were machined as-welded to evaluate real fatigue characteristic including stress concentration at weld joint, and tests were carried out. In addition, the specimens which don't exhibit stress concentration were compared with them. For the as-weld type specimen, the number of cycles-to-failure decreased because of the stress concentration but the fatigue life of JK2LB as weld joint satisfies the ITER CS lifetime requirement of 60,000 cycles.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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